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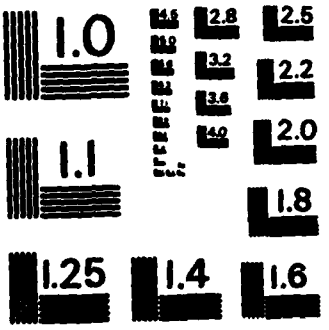

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This research has dealt with the modeling and solution of rotary-wing dynamics. In the modeling area, it deals with elastic-blade models, ways to introduce rotor-body coupling, aerodynamic behavior near bladetips, and the modeling of dynamic stall. In solution strategies, we have concentrated on new and improved Floquet methods, on innovative trim methodologies (such as auto-pilot and periodic shooting), on efficient formulation of equations, and on lifting-line and lifting-surface meshes. We have awarded 5 Master of Science and 1 Doctor of Science degrees to persons working on the project.

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EFFECT OF DYNAMIC STALL AND ELASTIC PARAMETERS ON THE FUNDAMENTAL MECHANISMS OF HELICOPTER VIBRATIONS

Final Technical Report

by

David A. Peters
Principal Investigator

1 September 1985

U.S. Army Research Office
Grant No: DAAG-29-83-K-0133

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1. Introduction

This final report covers 2 years of ARO-sponsored research into the fundamental behavior of rotor dynamics. The original proposal was for 3 years, but the third year is now to be done under a new grant. Thus, this report covers only a portion of the originally-proposed work. In this final report, we will summarize the work done, including publications and scientific personnel; and we will provide pertinent technical descriptions of each major area we have pursued.

The philosophy of our research has been to increase the fundamental understanding of those dynamic and aerodynamic phenomena associated with the helicopter. Our approach has been to follow three intertwining lines of research. The first of these is the line of mathematical modeling. Here, we wish both to synthesize and refine mathematical models for various, isolated rotorcraft phenomena, and to learn to couple them together in a systematic way. This is the building-block approach we have followed. The second line of inquiry has been in the development of solution methodologies for these equations. Here, certain solution strategies work better for certain models; and some modeling techniques require new solution strategies. We look specifically at methods that magnify our insight, are computationally efficient, and that can be extended to large-scale systems.

This leads, then, to the third thread of research: basic physical insight. Of course, because we deal with isolated components or with simplified couplings, we do not intend to be able to make predictions on helicopter stability and response that would be applicable to detailed design studies. On the other hand, we do expect our methods to be predictive of the behavior of simplified research models, such as those used by the Army Research and Technology Laboratories. Furthermore, we believe our results give qualitative insight into the physical phenomena present in production rotors. Thus, we try to involve all three elements in our research effort

2. Statement of Problem

The objectives and scope of this work are as follows:

1) To discover the basic relationships between blade structural parameters and the flap-lag-torsion airloads that result.

2) To determine the extent to which rotor-body coupling affects inplane loads and overall helicopter vibrations.

3) To develop our basic trim procedures to the point at which they can be applied to large, state-of-the-art rotor response program.

4) To determine the effect of dynamic stall on the rotor airloads and on the basic trimming methods.

5) To investigate other methods of obtaining time histories of rotor response, including Hamilton's Law of Varying Action.

Before proceeding to the details of each objective, it is informative to outline the scope in each task. With the exception of item 3, the above objectives are not aimed at the quantitative prediction of helicopter response. They are aimed at obtaining fundamental insight into how rotor vibrations develop and into how they can be efficiently calculated. Thus, in item 1 we consider a simple elastic-blade model with elastic flap, lag, and torsion. Although other, more sophisticated flap-lag-torsion models certainly exist, they have not been obtained under the same assumptions nor with the same purpose in mind as ours. Thus, we have proceeded slowly and carefully to make sure we understand the physical processes at each step.

In item 2, we are looking at a fuselage with 5 rigid body modes and 4 elastic modes (as in our prior work) but with a more detailed rotor model. Naturally, a true fuselage will have many more elastic modes; but we look at a generic frequency sweep that could be representative of several potential modes. Since we have already found that flapping motions drive inplane motions (while inplane effects flapping much less) we make several simplifying assumptions to increase the productivity (and physical interpretations) of the work.

Item 3 is the only area in which we approach the area of applications. These trim procedures are now fairly well understood in terms of theory, and the advancements now come through more sophisticated applications. Therefore, we have reformulated the trim procedures.

Item 4 is a new area of research that developed out of our dynamic-stall work. It is not in our scope to develop any dramatically new dynamic stall procedures. We merely take existing methodologies, investigate how they should be modified to be useful for simplified vibration analyses, and study the resultant effects on the types of calculations we are making.

Item 5 is also a new area of research which developed out of our prior trim investigations. For nearly linear systems, the trim method of periodic shooting is equivalent to finding and inverting the Floquet transition matrix. (An earlier solution method in our research also relied on Floquet theory for vibration analysis.) Thus, it is natural to look for more efficient means of finding the transition matrix. One possibility is the use of Hamilton's Law of Varying Action with comparison functions in time. In this research we study Hamilton's Law in detail with respect to convergence and efficiency.

3. Scientific Personnel and Degrees

Below is a tabulation of those who worked on this project during the past two years along with the degree they have pursued.

Personnel	Man-Months Effort	Degree Sought
David A. Peters	7.5	- (P.I.)
Gopal Gaonkar	3.0	- (C.I.)
Huang Ming-Sheng	15.0	Ph.D.
Swami Karunamoorthy	15.0	D.Sc.[5]
Danny Chiu	14.0	M.Sc.[2], Ph.D.
Amir Izadpanah	13.0	Ph.D.
Robert Longabaugh	5.5	M.S.
Liliana Ventura	3.0	M.S.[5]
Steve Slocum	0.5	M.S.
James O'Malley	-	M.S.[4]
Jack Ort	-	M.S.[3]
M. Chouchane	-	M.S.
Timothy Ryan	-	M.S.[1]

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[1]Received December, 1983

[2]Received May, 1984

[3]Received August, 1984

[4]Received December, 1984

[5]Received August, 1985

Thus, 2 professors and 11 students worked on the project for a total of 76.5 man-months. There were 5 Master of Science degrees and 1 Doctor of Science degree awarded.

4. Publications and Reports

1. Peters, David, "Toward a Unified Lift Model for Use in Rotor Blade Stability Analyses," presented at the 40th Annual National Forum of the American Helicopter Society, May, 1984; Journal of the American Helicopter Society, Vol. 30, No. 3, July 1985, pages 32-42.

2. Pitt, Dale M. and Peters, David A., "Rotor Dynamic Inflow Derivatives and Time Constants from Various Inflow Models," Ninth European Rotorcraft Forum, Stresa, Italy, Sept. 1983, Paper No. 55.

3. O'Malley, James P., Izadpanah, Amir and Peters, David A., "Comparison of Three Numerical Trim Methods for Rotor Airloads," Ninth European Rotorcraft Forum, Stresa, Italy, Sept. 1983, Paper No. 58.

4. Huang, M-S and Peters, David A., "Coupled Rotor-Body Vibrations with Inplane Degrees of Freedom," Proceedings of the 2nd Decennial Specialists' Meeting on Rotorcraft Dynamics, Ames Research Center, Nov. 7-9, 1984.

5. Peters, D. A., Kim, B.S., and Chen, H-S, "Calculation of Trim Settings for a Helicopter Rotor by an Optimized Automatic Controller," Journal of Guidance, Control, and Dynamics, Vol. 7, No. 1, Jan.-Feb. 1984, pp. 85-91.

6. Gaonkar, Gopal H. and Peters, David A., "A Review of Dynamic Inflow and Its Effect on Experimental Correlations," Proceedings of the 2nd Decennial Specialists' Meeting on Rotorcraft Dynamics, Ames Research Center, Nov. 7-9, 1984.

7. Peters, David A. and Ventura, Liliana, "Application of Various Solution Techniques to the Calculation of Transonic Flutter Boundaries," Proceedings of the ASME 10th Biennial Conference on Mechanical Vibration and Noise, Cincinnati, Ohio, Sept. 10-13, 1985.

8. Izadpanah, Amir, "Calculation of Floquet Stability by Generalization of Hamilton's Law to a Bilinear Formulation," Second-Place winner in the Robert L. Lichten Competition, AHS Forum, May 1985.

9. Ryan, Timothy, "Effects of the Fuselage on Helicopter Trim by an Iterative Harmonic Balance," Second-Place Winner in the Robert L. Licten Competition, AHS Forum, May 1984.

10. Ryan, Timothy, Effects of the Fuselage on Rotor Trim by an Iterative Harmonic Balance, Master of Science Thesis, Washington University, December 1983.

11. Chiu, Yih-Wan (Danny), An Investigation of Loss of Lift and Increased Drag Near Wing Tips, Master of Science Thesis, Washington University, May 1984.

12. O'Malley, James A. III, Correlation of Rotor Performance Through the Application of Four Trim Iteration Methods, Master of Science Thesis, Washington University, December 1984.

13. Karunamoorthy, Swaminathan, Use of Hierarchical Elastic Blade Equations and Automatic Trim for Helicopter Vibration Analysis, Doctor of Science Thesis, Washington University, August 1985.

14. Ventura, Liliana, Application of Various Solution Techniques to the Calculation of Transonic Flutter Boundaries, Master of Science Thesis, Washington University, August 1985.

5. Summary of Results

In this section, we summarize the results of our research through August 1985. Recall that we have completed only two years of a three-year effort. Thus, some of the tasks have taken a slightly different turn due to exciting results obtained during the research. The new direction of these tasks is mirrored in the new research grant, recently awarded to the PI through Georgia Institute of Technology. Because, this research project is ongoing at another institution, this summary will be brief. Details may be found in the references. (Reference numbers in this section refer to the publication numbers in Section 4.) Below, we list progress in each of the five proposed areas.

5.1 Torsion

The first area to be considered is the area of elastic torsion. Our work in this area is found in Reference 13). We have added elastic torsion to our equations and have documented these equations in said reference. Several important features distinguish these from other elastic, flap-lag-torsion equations in the literature. First, the ordering scheme used in the equations is based on the physical properties of representative rotor blades. Second, the equations are given in a hierarchical manner such that one can retain varying orders of terms as desired. Third, the equations are derived in forward flight with complete accounting for curvilinear coordinates, warp, and nonlinear virtual-work terms. Fourth, the equations are all written down in one place such that they can be checked term by term against past and future work. The highest order equations retain all known terms from previous work.

In addition to the development of these equations, we have successfully coded them and have obtained numerical solutions. Within the framework of this portion of the work, we have developed a new family of polynomials for use in the Galerkin analysis. These polynomials are orthogonal on -1 to +1, are normalized, and match the boundary conditions of uniform beams. A good portion of our work was devoted to the development and documentation of these polynomials. Furthermore, as we developed numerical solutions to the equations, we discovered that a very accurate trim procedure was required. Thus, we applied the automatic pilot to the equations with excellent success.

Due to the increased effort in polynomial development and in trim procedures, we have not performed as many vibration calculations as we originally planned. Thus, our present intent is to wait until dynamic stall is added to the model before we do the detailed, parametric studies.

5.2 Rotor-Body Coupling

In the area of rotor-body coupling, we have pursued two major lines of research. The first of these is the effect of rotor-body coupling on helicopter vibrations. The results of this work are partially given in Reference 4. In that reference, parametric studies show the effects of structural parameters on body vibration with a rigid-blade, flap-lag model of the rotor and with 9 fuselage degrees of freedom. Since then, we have developed the model for an elastic rotor and have begun the coding. As it turns out, the increased complexity of the elastic equations has forced us to develop a new iterative procedure for the harmonic-balance approach. Presently, it appears that this procedure will be successful.

In a second area, we have continued our long-term interest in dynamic inflow and in its effect on the stability of coupled rotor-body modes. Reference 2 describes the model that we have developed, and Reference 6 provides comparison of stability and response calculations with experimental data. The correlations are no less than spectacular, and they establish our model as the premier model for dynamic inflow.

5.3 Dynamic Stall

An important part of our research into rotor vibration has been the modification of the ONERA dynamic stall model for use in rotorcraft problems. Reference 1 provides the theoretical foundation for the stall model that we are now using. It is a completely unified model in that quasi-steady and quasi-static aerodynamics can be recovered from it. Furthermore, it is written in terms of U_p and U_T with no small-angle assumptions. Thus, it is easy to implement. Finally, it is formulated in terms of nonlinear differential equations that can be linearized for use in eigenvalue analyses. Future work is needed to modify the ONERA pitching-moment model.

In an important spin-off of this work, we have found the concepts inherent in the stall model can be used to model unsteady, transonic aerodynamics. References 7 and 14 summarize this work. Although much of the work was done under Air Force sponsorship, a good portion was done under the ARC grant. In particular, the problems encountered in that work lead to a better understanding of our dynamic stall model and a better understanding of our trim method called "periodic shooting". We have now showed that periodic shooting can be used for stability computations when a particular rotor parameter is taken at an unknown along with initial conditions.

5.4 Trim Methodologies

This brings us to the next area of research, trim methodologies. Several tasks have been performed within this category. The first task to be discussed is the addition of fuselage degrees of freedom to the trim process. References 9 and 10 outline our progress in this area. Several important insights have resulted. Included among these are the facts that: 1) several different trim definitions can be used, each with a physically-meaningful interpretation and each with a well-defined mathematical formulation, 2) fuselage aerodynamic derivatives need to be defined in terms of nonlinear definitions of Euler angles, and 3) convergence can be rapid provided an appropriate strategy is used.

In a second area of work, we have successfully applied our trim methods to large, production-type rotor response codes. Basically, we have three trim procedures, each of which having its own strengths and its own realm of applicability. One is the harmonic balance, one is the method of periodic shooting (References 7 and 14), and one is the automatic pilot (Reference 5). In Reference 13, the automatic pilot was successfully applied to a fairly complicated rotor model. In References 3 and 12, all the methods were applied to an Army Air-Loads program. The results are compared with wind-tunnel data with excellent agreement. Also, these methods have been applied successfully at Georgia Tech and at Kaman Aerospace Corp.

A third development within trim methodologies has been our study of tip-loases for rotors. (The lift and drag near a rotor tip have a large effect on the trim of the rotor.) Reference 11 outlines the initial phase of the work, in which the lift near a wing tip was examined via lifting-line theory. Since the, we have expanded the lifting-line analysis to hovering rotors; and we have now developed lifting-surface models of rotors in hover. As a practical development, our results not only show excellent correlation with measured data, but they display a greater computational efficiency than previous work.

The improved efficiency has come from an important finding. In particular, we have learned that, under certain conditions, lifting-line and lifting-panel methods can result in errors that do not go to zero as the mesh is refined. One such condition is where a mismatch in panel sizes occurs at some node, and a second condition is where a uniform mesh is used near the tip. As a result of these observations, we have discovered the optimum way to size the panels in a lifting-surface theory. Furthermore, we have learned to replace finite-difference solutions with Fourier solutions in some cases.

5.5 Floquet Theory

The last area to be discussed is that of Floquet analysis. We have had two major projects under this heading. First, we have been developing a multi-blade transform that is applicable to rotors with an even number of blades. The existing multiblade transforms can be applied to such cases, but one coordinate always remains in the rotating system. Consequently b/2-harmonics remain in the equations. The situation is most critical for a 2-bladed rotor (b=2) for which the old method is completely degenerate. Our new method, based on an extension of Jack Hoffmann's work, overcomes this problem; and only b-harmonics remain. In two major developments of this multi-blade work, we have: 1) developed a matrix formulation such that the cumbersome algebra of such transforms is avoided, and 2) compared the efficacy of the new constant-coefficient approximation with previous work. In this latter case, we have found the results to be much better than expected.

In the second Floquet project, we have extended Hamilton's Law of Varying Action to a bilinear formulation. The resultant finite elements in time are then used to find the Floquet Transition Matrix. Several investigators have been applying Hamilton's Law, but the results often diverge and computational efficiency is low. We have proven with mathematical rigor that present applications are incorrectly formulated; and, thus, they will sooner or later

diverge for some case. We have also proven, however, that the correct formulation (which we have developed) is categorically convergent; and we have demonstrated this numerically as well by solving problems which (in previous work) had diverged.

The results of this work are two-fold. First, it has resulted in an entirely new way of looking at dynamics problems (from a variational point of view). Second it has resulted in computational efficiencies that rival those of time-marching. We are very excited about this work.

6. Conclusion

In conclusion, the work has proceeded successfully on several, widely varying topics. This multi-disciplinary aspect of our work has resulted in interactions that would be otherwise impossible. We believe that this synergism among the five areas has been one reason that such exciting results have been obtained.

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